Northeastern University Planetary Articulating Water Extraction System (NU PAWES):
A Proposal for Autonomous Extraction of Water from the Martian Surface

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1- Introduction

A manned mission to Mars is the next major space development milestone for humanity. The success of such a mission relies in part on designing a reliable and efficient water collection system suited for the Martian environment. Extraction of in-site water resources will not only prolong the missions of human crews but also enable Hydrogen based fuel generation for the return journey.

To accomplish this engineering challenge, our team proposes a fully autonomous system capable of drilling, melting, and collecting water from beneath the Martian surface. The system will function as follows. After deployment on the Martian surface, the drill bit will position itself above the surface and will drill into the overburden and ice. Once a hole of depth 1.25in is made in the ice, the drill will be lifted, and the system will shift along the x-axis to align the extractor above the hole. The extraction subsystem will then be lowered into the drilled hole. The extractor nozzle will produce heat while the articulating head moves to maintain contact with the ice. The liquid water will then be pumped out and transported to the filtration system. The extractor will be lifted out once it has melted and collected all the ice within reach. The system will then autonomously realign to drill a second hole and repeat the process. Control station software will control and monitor the system as it transitions from one state to the next and perform emergency recovery in case of system error. The total system will form an iterative process for the extraction and melting of subsurface ice, forming the foundation for an eventual implementation on Mars.

2 – Proposed Mechanical Design
2.1 - Structural Overview

The overall structure of the system is comprised of two elements. The first element is the stationary frame, and the second is the tool mount carriage. The stationary frame was designed based on a standard triangular truss to improve stability, while minimizing the weight of the system. The frame is made from an extruded aluminum top and base, with four steel threaded rods holding up the sides. Additional cables are mounted diagonally to prevent any unwanted movement of the frame. The team determined that two axes of movement make the system adequately versatile in the context of the challenge time constraints. Drilling holes across the entire surface of the block was deemed unrealistic due to time constraints. Instead, the structure allows for movement across the center of the ice block. The dimensions of the frame are 38x38x50in, meeting the size constraints. The test station mounting interface is depicted in Figure 2.2. At each of the mounting bolts, an external 80/20 fastener is clamped down, and is able to adjust in multiple directions depending on test station tolerances.

The second structural element is the tool mounting carriage. This element is a rectangular frame made of 80/20 extruded aluminum beams, and can be moved along the x-axis. The carriage is fixed to the top and bottom of the frame to ensure movement is controlled precisely. The overall mass of the system is calculated using published motor masses [2], as well as material properties in SolidWorks to estimate a total mass of 45kg excluding wiring and electrical components.
2.2 - Positioning Subsystem

The positioning subsystem was designed around movement of a traditional 3-D printer without freedom in the y-axis. Movement in the x-axis is controlled by a belt and pulley system driven by a stepper motor. Positioning in the z-axis uses lead screws and is also stepper driven. Stepper motors are used to ensure precise positioning in aligning the drill bit, as well as the extractor. The tool mounting carriage is attached to the belt at the top of the frame, and is guided on the bottom by a linear slide for additional stability. For motion in the z-axis, the drill and the extractor are independently driven, to allow for ease of mechanical construction and control in the future. Drilling and extraction systems are fixed to independent linear guide rails and separate lead screws.

2.3 - Extraction Subsystem

The ice melting system and water removal system are integrated in the Extraction Subsystem, to be the distinguishing aspect of the team’s design. Its primary characteristic is a subsurface articulating heating apparatus which is inserted into the hole created by the drill bit. The articulative motion of the heating tip allows constant contact heating of the ice block - a method of heating that allows for more efficient heat transmission than other methods. This heating tip doubles as a primary filter and nozzle, and can be seen in Figure 2.5.

Once lowered to contact the surface of the ice block, the temperature of the nozzle will be held constant at near-boiling temperature. The larger the contact area, the faster heat is drawn from the heating tip. Our preliminary test results showed that when the tip temperature begins to rise while input power is held constant, heat conduction is no longer optimal and the heating tip has lost direct contact with the ice. Therefore, the tip should be advanced further into the ice.

In addition to simple downwards motion, the articulating nozzle has an extra two degrees of freedom. Three tensioning wires allow the articulating nozzle to bend throughout a cone-like volume. By either pulling or extending each wire at the top of the extractor, the direction and magnitude of the bend can be controlled. Instead of melting straight downwards, the nozzle traces a spiral path while lowering the tip. This allows an effective ice melting diameter far greater than the diameter of the augured hole. The precise hole shape is shown in Figure 2.3 and the melting volumes associated with certain tip angles are shown in Table 2.4. The position of the nozzle is determined by the ratio of lengths of the three tensioning cables. These cables will be extended and contracted via three linear drivers above the extractor.

A mockup flexible segment was modeled and 3D printed for proof-of-concept. The model was used to explore the functioning principle of the extractor tip.

The nozzle is made of aluminum and is heated by three power resistors, which are rigidly attached to the nozzle body. The nozzle acts as a heatsink for the resistors, which are specifically designed for thermal conductivity. Thermal paste is also used to enhance heat transmission.

In order to test the functionality of the heating tip, a mockup heating element was created and tested following a predefined test procedure. The block was chosen to have comparable surface area and volume to the nozzle. Power was supplied and monitored with a variable DC power supply. The temperature of the block was measured with a thermocouple and multimeter. The test was timed on a stopwatch. Test results were measured in mL/time, and several scenarios were tested to determine the most efficient way to melt the ice. The experimental setup can be
seen below in Figure 2.6. Simulated situations included applying force on the block, moving it across the surface, allowing the block to sit surrounded by water, and having the block heat near, but not in contact with the ice. The test results confirmed a high potential melting rate of the proposed system. Under 120W, the heating block was able to melt 75 mL in 5 minutes while in constant contact with the ice. This is equivalent to 900 mL of water melted per hour, approximately double that of the 2016 challenge finalist’s final results. A control test showed that only 10 mL of water melted due to the ambient temperature of the room. During the challenge, much more than 120W will be available for the heating element, so theoretical melting rate when implemented in the system is higher than the test showed.

Each heating element has an individual thermistor and power chain, so that they can each be held at a safe temperature. The power and sensor wires will extend up the extractor shroud and to the control board.

The initial length of the water extraction tube is aluminum, but higher up the heat becomes less intense so the shroud transitions to temperature-stable plastic. The internal extraction tube is lowered to negative pressure by a pump at the top of the extractor, and through this the water is suctioned out of the ground.

The pump is a peristaltic pump. Peristaltic pumps can handle dirty water and sediment, and will not get fouled like other pump designs. Additionally, they have the ability to self-prime, which is necessary for initiating water collection. The peristaltic pump is also capable of operating in reverse, which promotes de-clogging of the primary filter, explained in the next section. The pump will bring the pressure in the water tube low relative to the atmosphere, and the water will be forced up the tube. Once the water reaches the pump, it travels towards the filtration subsystem.

2.4 - Filtration Subsystem

To filter the mixed water collected, the team has designed an original dual gravity and flocculation system that provides a unique solution to yield clean water without the use of a physical filter. The initial filtration will be from a coarse screen on the tip of the nozzle to prevent large sediment particles from entering the system. The secondary stage is shown in Figure 2.7 to the right. The pump (purple) draws extracted water to the staging zone blocked off by three valves (yellow). The top valve then seals the storage zone from the open end of the nozzle. The bottom valve opens to release collected debris when sediment levels are high, and the left valve expels clean water to the collection bucket. In 2016, the team did in-depth testing of filtering an overburden and water mixture through flocculation as can be seen in Figure 2.8. Due to the physical properties of clay, the overburden maintains a slight negative charge. Given that the overburden will hold approximately 30% clay, sediment filled water to be filtered can thus be manipulated by positively and negatively charged conductors (red). When water fills the storage tank, the valves seal off, and the conductors turn on. The clay moves to the bottom due to gravity and flocculation. Filtered water then avoids potential refreezing (especially in a colder Martian environment) by heat released as a side effect of electrical conductors. After multiple filtering cycles releasing clean water, water is removed from the tank for use, and the refuse collected is released by opening the bottom valve. There will be a slight loss of water in this process, but this loss will be significantly less than the water required to periodically backwash an internal filter.
2.5 - Extraction Path-to-Flight

The primary consideration for extraction path-to-flight is the sublimation of the ice and evaporation of water inside the drilled hole, as the mean temperature on Mars is -65°C, and the average atmospheric pressure is roughly 0.01bars [4]. Additional design elements would need to be taken to prevent the escape of heat, sublimation of ice, and rapid evaporation of water under these conditions. This could be accomplished using a sheath that would retract from the system into the hole when drilling and extracting. The sheath would have an expanding seal at the entrance to the hole to prevent water vapor from escaping. The hole could then be pressurized to ensure no water vapor escapes. However, this method may require a significant amount of energy to pressurize the entire cavity, and the seal could have variable effectiveness for different holes. Thus, an alternative may be to capture water vapor with the sheath. Water vapor would travel up the sheath and into an enclosed chamber. The chamber could then be pressurized to condense the vapor into liquid water.

The pumping system would also need minor modification for operation on Mars. The concept of the peristaltic pump is still feasible, but the pump would either need to be able to create a stronger vacuum or be located closer to the nozzle. While the lower gravity on Mars allows water to rise higher under a vacuum, the lower atmospheric pressure reduces the pressure differential acting upon the water. The net result is that water cannot rise as high in the tube, and may not reach the pump. This problem can be resolved by moving the pump into the extractor itself. The lowered pump will be able to prime itself with water, at which point it begins to push the water upwards with positive pressure - a much more effective method of raising water than suction.

2.6 - Drilling Subsystem

The drilling system is designed with the goal to drill a hole as quickly as possible while excavating the appropriate space for the extractor for the purposes of this challenge. To drill as quickly as possible and limit the power draw of the subsystem, the team established that it would be best to drill a narrow and shallow hole. Considering size, time, and power constraints, the drill bit has a 1.25in OD to offer a slight tolerance around the 30mm extractor system. The drill bit’s shaft length is 36in, with an active threaded area of 31in. The actual hole depth is intended to penetrate the ice only 1 inch. Based on ice melting tests, the team has deemed that the melting system can travel into the ice by melting a descending path, so there is little benefit to drilling a large distance into the ice. Despite only minor drilling into the ice, durability is an important factor. The team looked into the existing Ice Breaker drill, and determined that a concrete masonry bit is a low-cost alternative that would serve as an appropriate down scaled version for the Challenge [5]. Masonry bits are designed to drill through hard surfaces, and will have no difficulty drilling through the clay, sand, gravel overburden, and even ice [3]. Initial testing with various sized masonry bits into dirt and sand environments proved effortless drilling into the overburden. Figure 2.9 depicts our testing with undersized bits to determine the effectiveness of masonry bits. This experiment provided the team with a baseline understanding of drill behavior, as well as proof of concept for drilling with masonry bits into the overburden. A non-stick coating will be applied to the surface of the drill to prevent overburden from getting lodged within the threads of the bit.

The motor chosen for the drilling system will be a standard rotary drill with high speed and low torque. Based on results from the 2016 challenge and preliminary research, a torque of 5-10Nm will be adequate, and follows the 100N WOB (Weight on Bit) requirement. The WOB itself will be measured using a load cell at the mounting fixture between the drill and the lead screw.

2.7 - Mechanical Path-to-Flight

There are a few important considerations to take when designing the system for operation on Mars. The first consideration is that if any component of the system were to break, it may not have the capacity to be replaced for up to two years, accounting for Mars launch windows. Redundancy should be considered, and the materials used in the system must be optimized to Martian conditions. Currently, titanium is used for the body of the Curiosity rover, and similarly capable materials will need to be integrated in a Mars-ready system. Additionally, operating in a Martian environment may require higher mobility. To achieve this, the system could be mounted on a mobile platform or rover that would allow access to new areas once all reachable water has been extracted. Alternatively,
the articulating extractor can extend horizontally within the ice to reach even more liquid beneath the surface. Lastly, the design of the drill could be improved to handle a variety of materials, and have self-cleaning mechanisms on Mars. Drill designs like the Ice Breaker drill could be a viable replacement for use on Mars the Earth friendly bit proposed [5].

3 – Proposed Electrical Design

3.1 - Power Distribution and Management

The voltage the system uses must not be over 120V and draw no more than 10A. The distribution of power to the system is controlled through power relays controlling each element of the system. This ensures power constraints are adhered to by not supplying power to elements that are not in use. To begin, an overall “kill-switch” takes the form of a relay placed immediately after the AC outlet in the circuit. This part is capable of stopping all function of the system to prevent damage or danger in case of failures in the electrical system. The circuit then splits into two branches, one leading to a DC power converter, and one leading to a relay and then the drill. Microcontrollers control all the relays in the electrical sub-system. The onboard computer controls the microcontrollers, and additionally receives data from the Sensor Suite on the system.

The microcontrollers have the responsibility of controlling and monitoring the heating element, the drill, the motors, and the pump through the use of power relays. The relays for each subsystem will be tailored to specific current requirements for each part. Every subsystem is designed for minimum current draw, except for the heating system which needs maximum power to melt the ice as fast as possible. The heating element will be controlled through a MOSFET-type transistor, which allows a high frequency PWM signal from the Arduino to precisely control the power consumed by the heating element. The microcomputers provide on-board control of the system, record data from the Sensor Suite, and manipulate the mounted cameras on the apparatus. The microcomputers are powered at all times to record and send information, so they draw current at all times.

The DC power converter is needed to drive the motors for motion in x and z axes, as well as the motors controlling the movement of the articulating extractor head. The pump and heating element also use DC power. The direct drive motor for the drill relies on AC power. When the extractor head is melting, it only requires movement performed by the cable motors. Sending more current to the heating elements will minimize the time the melting phase takes, which is the primary limiting factor in the water extraction process.

3.2 - Power Monitoring

Monitoring the current draw of the system is extremely important in regulating each component’s usage, because current is the primary limiting operational constraint for this system. Thus, the power must be monitored in real-time through a Raspberry Pi that serves as the master on-board computer for the system. The Pi, running the Robot Operating System (ROS), will be connected to a current monitor individually testing the current draw of the drill, pump, and extractor. This data is accessible through the GUI at the remote computer.
To account for safety, the proximity of electrical components in the nozzle to water may present hazards if not addressed responsibly. The system will be reinforced using heat shrink and waterproof epoxy to ensure a water tight seal between electrical components and water.

3.3 - Electrical Path-to-Flight

Temperature and atmospheric differences between Earth and Mars are similarly integral when considering changes to the electrical system. High radiation effect on Mars [1] poses a threat to electrical system components. To account for this radiation, custom processors and microcontrollers would be fabricated with radiation shielding in mind for use on this system. All electrical system components would also require additional radiation shielding and insulation including wiring for the system. Sensitive components will need to be specially manufactured with environmental conditions in mind, including additional shielding from the other environmental forces such as wind, sand, and temperature fluctuations from day and night cycles.

To monitor the status of the system in Mars’ riskier conditions, low-power sensors, including additional cameras or optical sensors, would be implemented at a variety of contact points on the system. As the system is designed to operate completely independently, sensor data can be used to protect the system, and react to the increased number of external forces acting on the system in the Martian environment.

4 – Proposed Software and Control Design

4.1 - Software Architecture

The software sub-system is based on a multithreaded design, comprised of a master thread run on a control station laptop or desktop. This station communicates with the system via ethernet link to a Raspberry Pi on-board the system. This on-board processor runs threads controlling specific subsystems of the design, namely the positioning system, the Sensor Suite, and extraction subsystem. Threading control and memory allocation are supported by the Robot Operating System (ROS) framework. ROS allows for ease of communication between threads running on independent processors, as well as the necessary abstraction layers to implement autonomous functionality.

4.2 - Data Collection

Full autonomy of the system is achieved through real-time sensor feedback. The Raspberry Pi receives sensor input from the entire Sensor Suite including data from each motor, the heating element, the pump, and the drill. This data, as well as a view of the system from the on-board camera, is then communicated with the control station. The sensors facilitate fault detection in the system to prevent the failure of mission-critical elements such as the stepper motors, and most importantly, the system power consumption and WOB. The data collected about all aspects of the system inform the control team about the position of the dynamic elements of the system such as the moving extractor head and heating element. Additionally, this data contributes to a database of the behavior of the system, able to be analyzed for continual improvement of the system from testing.

4.3 - Control Systems

The system is controlled via a Graphical User Interface (GUI) displayed on the control station computer as seen in Figure 4.1. The GUI supports two main functions. The first is the manual monitoring of system data taken in by the Sensor Suite, accessible via the Information section. The second is the control of the system through the Control section.

The Information section of the GUI continually displays required parameters of WOB and system power consumption, as well as a live feed of video from an on-board camera, the current robot pose through a 3D rendering of the system, and information from other sensors on request. The Control section is the interface for the operator to access and manually modify motion and power distribution of the system, including the location and movement speed of Figure 4.1: User Interface Mockup
positioning system stepper motors, speed of drill motor, power allocation for each system element, control of the extractor, and control of the extraction pump system. In addition to making specific changes to the parameters of each subsystem, the operator can also initiate system state changes requiring multiple actions by different subsystems. For example, an all stop is constantly be available for execution by the operator. However, while all degrees of freedom will be available for control by the operator, intervening action should not be necessary due to the constant observation of the system parameters by the system’s autonomous monitoring system, outlined below.

4.4 - Autonomous Systems

The system functions with full autonomy thanks to two additional threads. These consist of a Data Monitor and a System Controller thread. The System Controller monitors the challenge time and data regarding the state of each subsystem to guide the system through its operational flow, as outlined in Figure 4.1. This allows for the system to autonomously accomplish each subtask in its drilling, extraction, and filtration process within the given challenge time. In order to achieve full autonomy, this will be coupled with a Data Monitor. The Data Monitor will process the data taken by the system’s Sensor Suite and determine if any parameters are out of intended ranges. These parameters include power consumption, WOB, and system pose to ensure no conflicts between the system’s moving components and the known environment of the test bed, and tuning extractor temperature using the PD components of PID control to prevent overheating of the extractor head. The Data Monitor relays information regarding potential system errors to the System Controller so it can take immediate action to correct and prevent system failures.

4.5 - Software Path-to-Flight

For operation on the Martian surface, the software system will need to be modified to account for any additional sensors added to the system. Additionally, functionality will have to be implemented to allow for long range wireless communication with Earth or another remote location. Finally, the autonomous decision making and processing should be further developed to deal with the extended range of variables that could cause system faults due to environmental factors, and the wear and fatigue of parts that the system will experience on Mars.

Figure 4.2: Software Process Flow

5 - Logistics

The project will be advised by Dr. Taskin Padir, Associate Professor of Electrical and Computer Engineering at Northeastern and director of the Robotics and Intelligent Vehicles Research Laboratory (RIVeR Lab). Dr. Padir currently leads a team sponsored by NASA to develop autonomy for the Valkyrie (R5) humanoid robot, has previous experience in RASC-AL, DARPA, and NASA Sample Return Robot challenges, and has proven a successful and effective advisor to numerous, past student projects.

Under the mentorship of Dr. Padir, the development, construction, and evaluation of this project will be conducted at Northeastern’s RIVeR Lab. This facility is equipped with the full range of necessary tools, protocols, and space to safely and effectively develop and test the proposed system. The RIVeR lab otherwise specializes in autonomous robots and intelligent vehicles, and researchers in these disciplines will be available to advise and monitor the progress of the system development. Northeastern, as well as Boston-area-based organizations such as Cambridge Hackspace, offer resources, workspaces, and equipment such as laser-cutters and PCB fabrication.

Sub-system development is led by the following team members: Daniel McGann, Software and Control lead; Benjamin Zinser, Mechanical System lead; Fizzah Shaikh, Electrical System Lead; and Andrew Panasyuk, Extractor System lead. Daniel has experience developing robot software since high school, including more recently
work with R.O.S. on another RIVeR project ORYX. Benjamin has led the design of multiple world-qualifying VEX competition robots on a low budget, and interned at Thales Visionix as a Mechanical Engineer. Fizzah has experience with embedded system design and power controls and has developed algorithms for a marine AUV sampler in Northeastern’s Environmental Sensors Lab. Andrew has captained a three-time world championship qualifying FIRST Tech Challenge team and has wide experience with additive manufacturing. Through the experience of our team leads as well as the skills, knowledge, and creativity of every member on our team, NU PAWES will have the abilities to for the effective development of our proposed system.

The intended development timeline to complete system integration and technical writing for documentation of the system by the deadline of May 20th is described in Figure 5.1. Steps to completion have been thoroughly considered, and the team is prepared to devote the necessary resources to fabricate and evaluate the system to completion.

References